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Mudge

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(54) **EDGE DETECTION IN IMAGES**

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(51) **Int. Cl.**

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G06K 9/46	(2006.01)
G06T 7/00	(2006.01)
A61B 6/00	(2006.01)

(52) **U.S. Cl.**

CPC ***G06K 9/4604*** (2013.01); ***G06T 7/0085*** (2013.01); *G06T 2207/10004* (2013.01); *G06T 2207/30016* (2013.01); *G06T 2207/30041* (2013.01)

(58) **Field of Classification Search**

USPC 382/100, 103, 106–107, 128–134, 140, 382/162, 168, 173, 181, 194, 199, 209, 232, 382/254, 266, 274, 276, 283, 291, 305, 382/312; 359/738; 348/65; 600/407, 473

See application file for complete search history.

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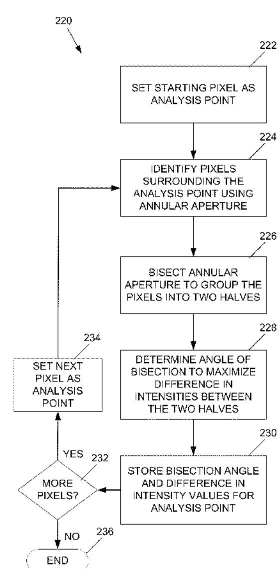
(57) **ABSTRACT**

An edge detection engine operates to scan an image to identify edges within the image. An annular aperture is used to locate the edges in the image. An output image is generated by the edge detection engine that identifies the locations of the edges found in the image.

17 Claims, 18 Drawing Sheets



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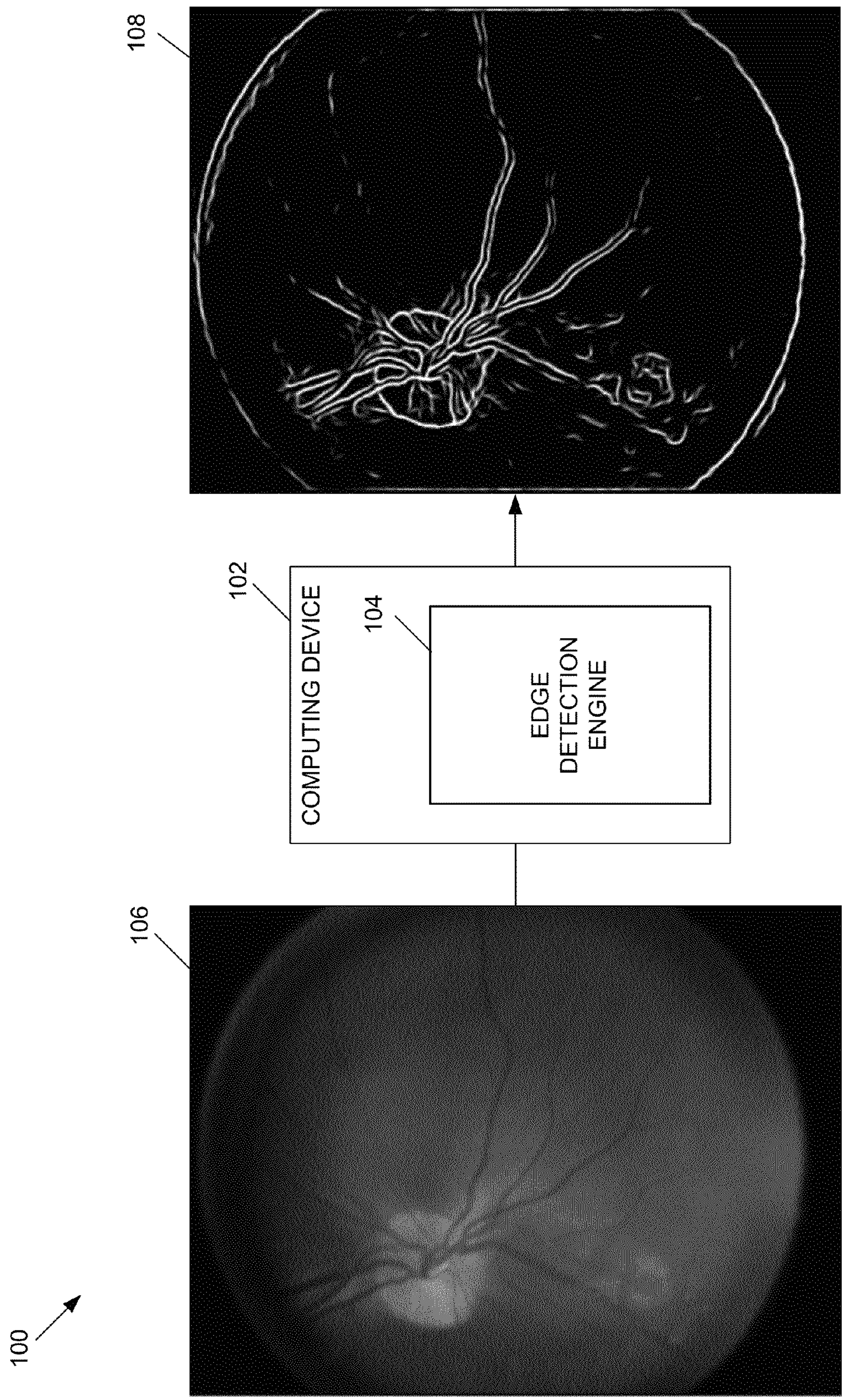


FIG. 1

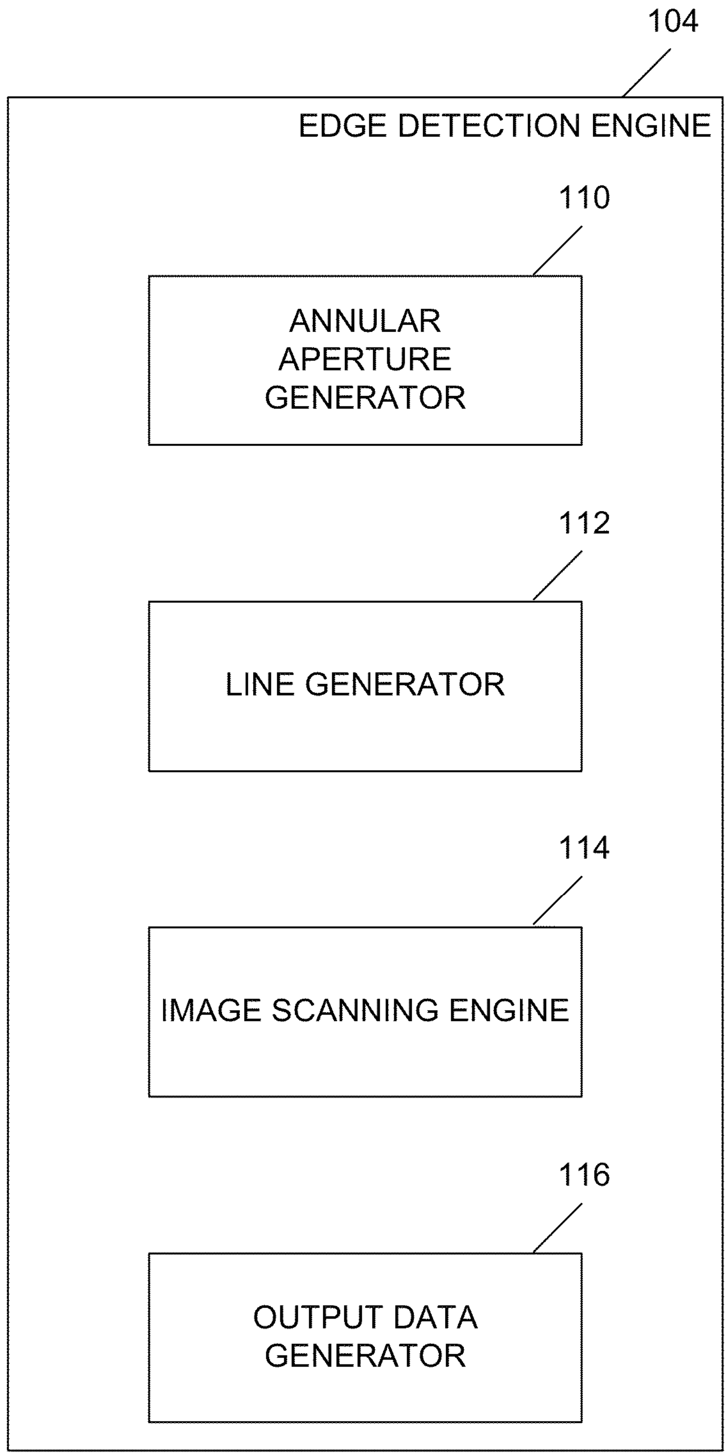

104
EDGE DETECTION ENGINE
110
ANNULAR APERTURE GENERATOR
112
LINE GENERATOR
114
IMAGE SCANNING ENGINE
116
OUTPUT DATA GENERATOR

FIG. 2

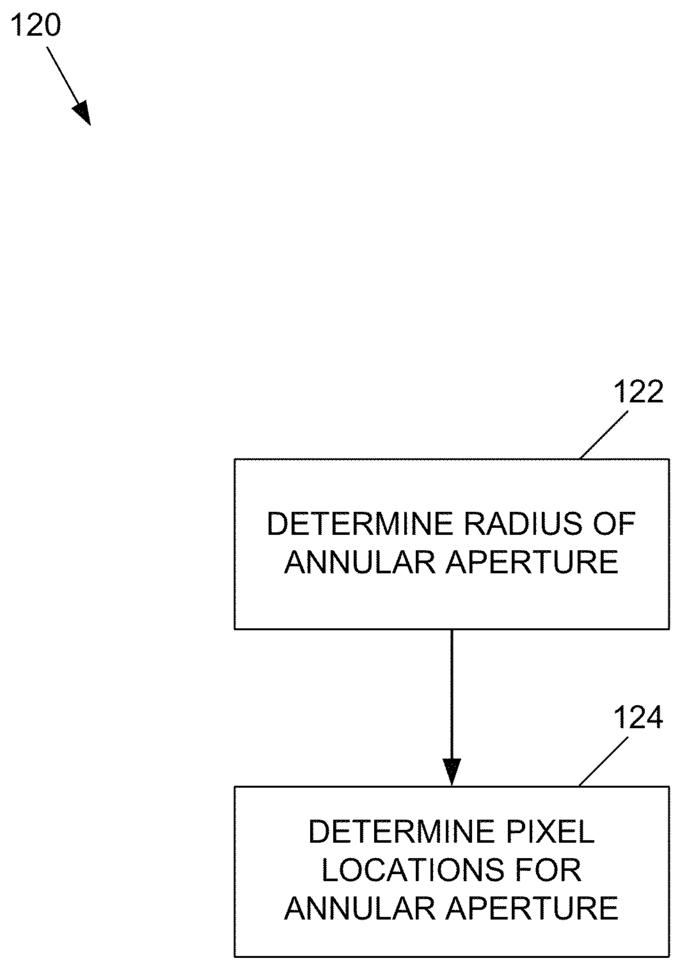

120
122
DETERMINE RADIUS OF ANNULAR APERTURE
124
DETERMINE PIXEL LOCATIONS FOR ANNULAR APERTURE

FIG. 3

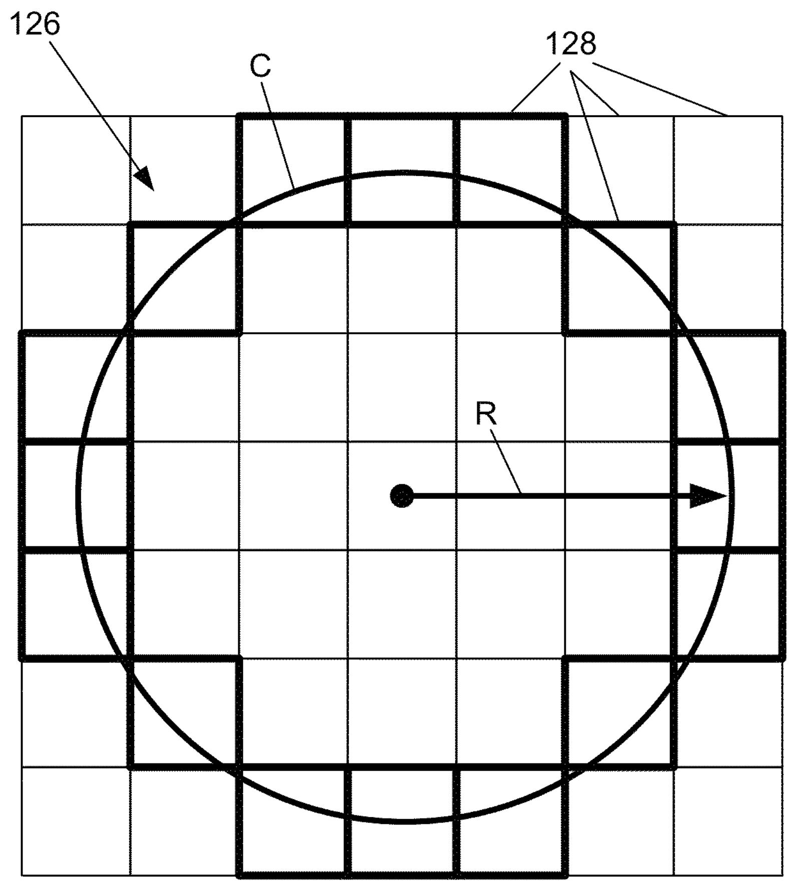


FIG. 4

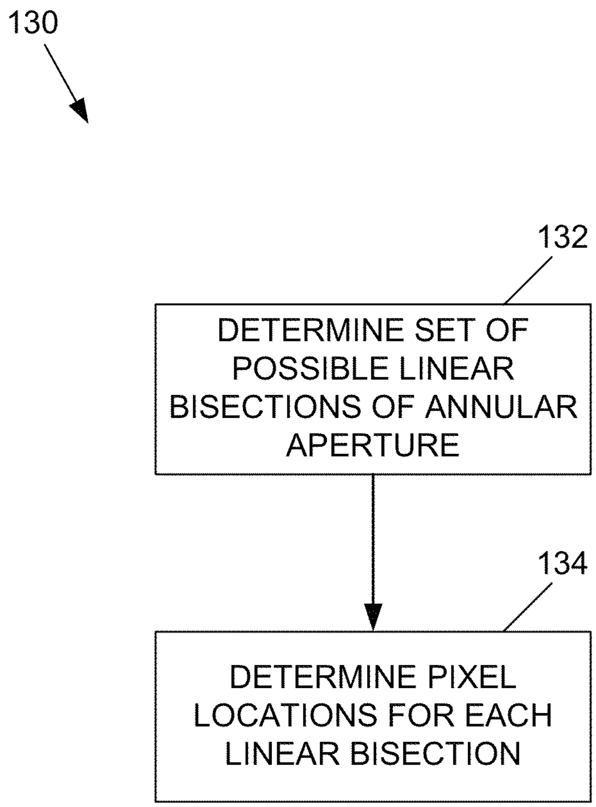
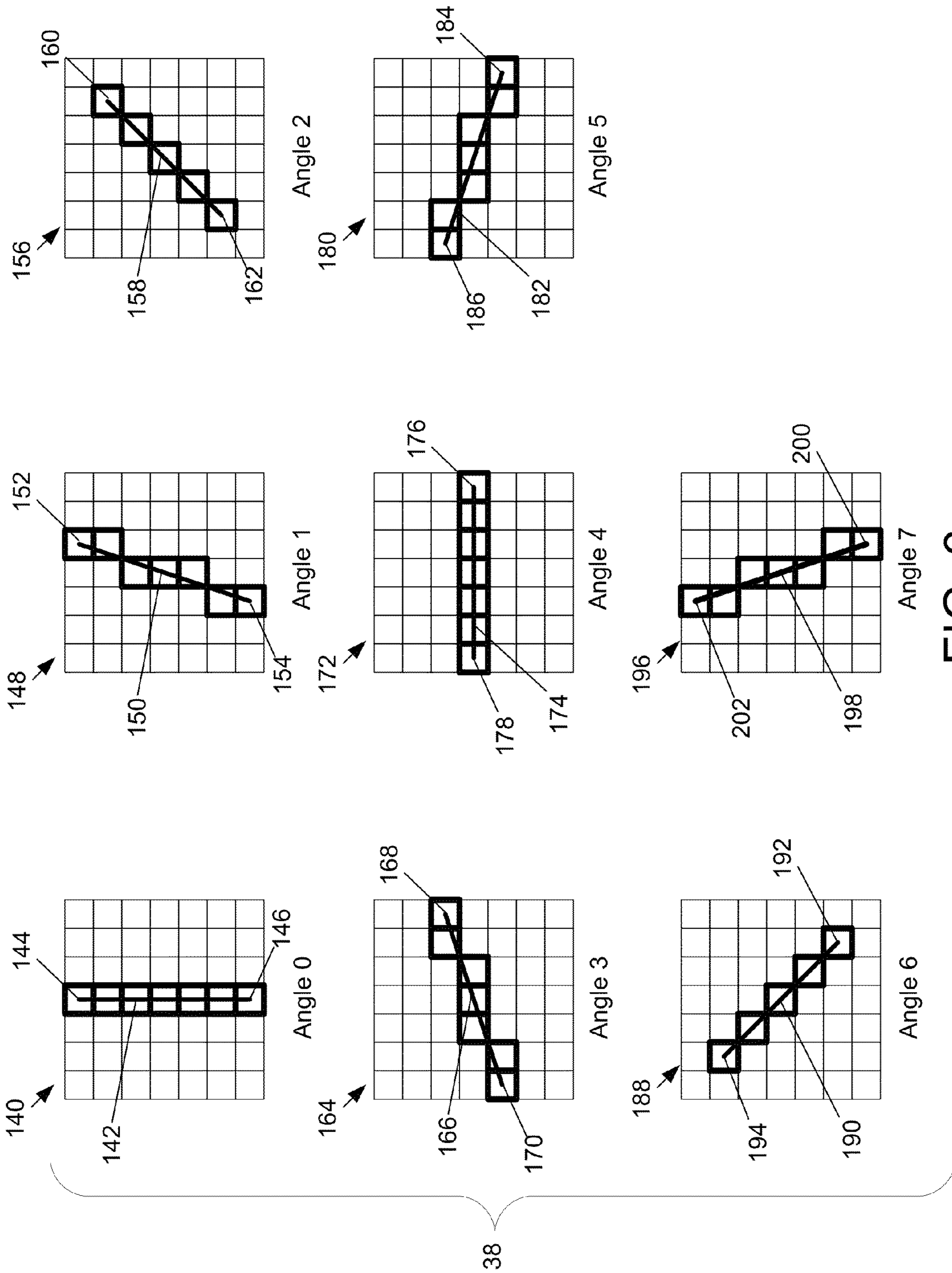

130
132
DETERMINE SET OF POSSIBLE LINEAR BISECTIONS OF ANNULAR APERTURE
134
DETERMINE PIXEL LOCATIONS FOR EACH LINEAR BISECTION

FIG. 5


Angle 0
Angle 1
Angle 2
Angle 3
Angle 4
Angle 5
Angle 6
Angle 7
138
140
142
144
146
148
150
152
154
156
158
160
162
164
166
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170
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174
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180
182
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200
202

FIG. 6

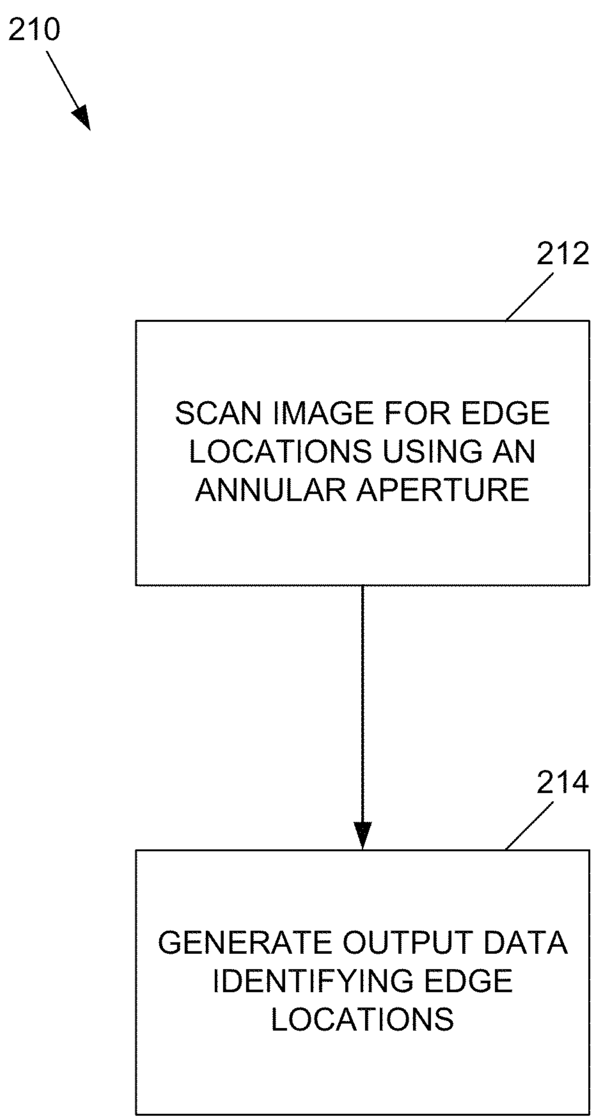
210
212
SCAN IMAGE FOR EDGE LOCATIONS USING AN ANNULAR APERTURE
214
GENERATE OUTPUT DATA IDENTIFYING EDGE LOCATIONS

FIG. 7

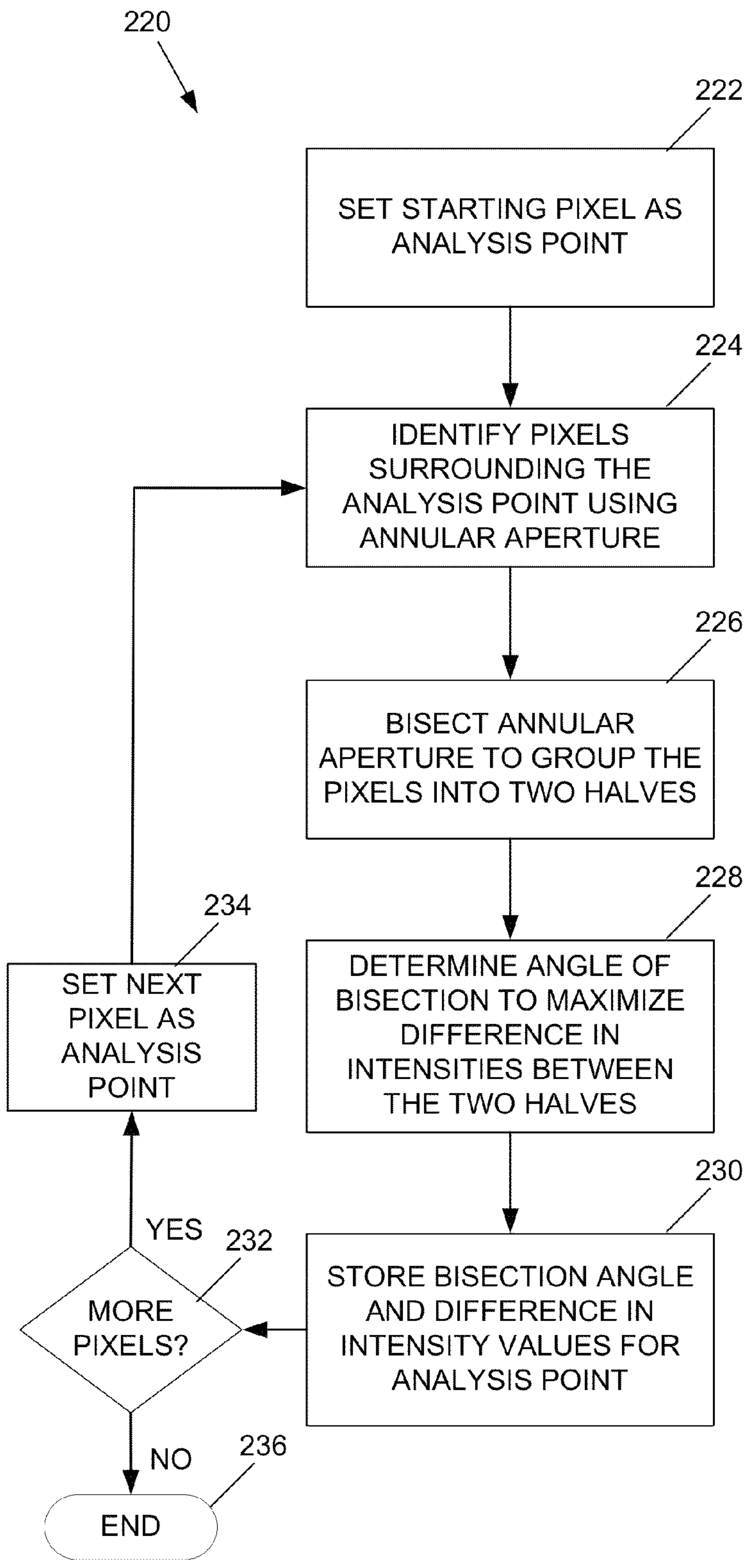
220
222
SET STARTING PIXEL AS ANALYSIS POINT
224
IDENTIFY PIXELS SURROUNDING THE ANALYSIS POINT USING ANNULAR APERTURE
226
BISECT ANNULAR APERTURE TO GROUP THE PIXELS INTO TWO HALVES
228
DETERMINE ANGLE OF BISECTION TO MAXIMIZE DIFFERENCE IN INTENSITIES BETWEEN THE TWO HALVES
230
STORE BISECTION ANGLE AND DIFFERENCE IN INTENSITY VALUES FOR ANALYSIS POINT
232
MORE PIXELS?
YES
234
SET NEXT PIXEL AS ANALYSIS POINT
NO
236
END

FIG. 8

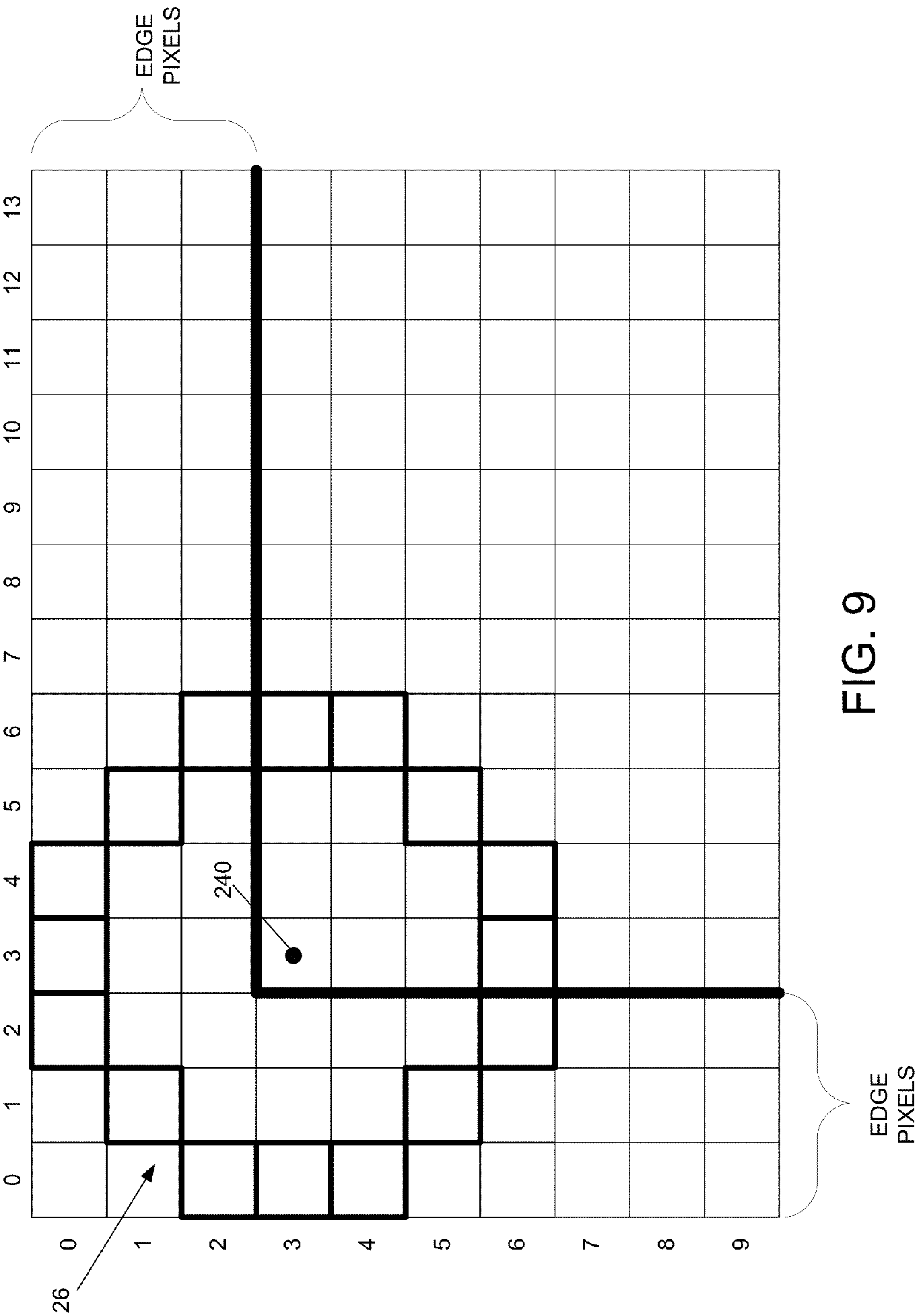

FIG. 9

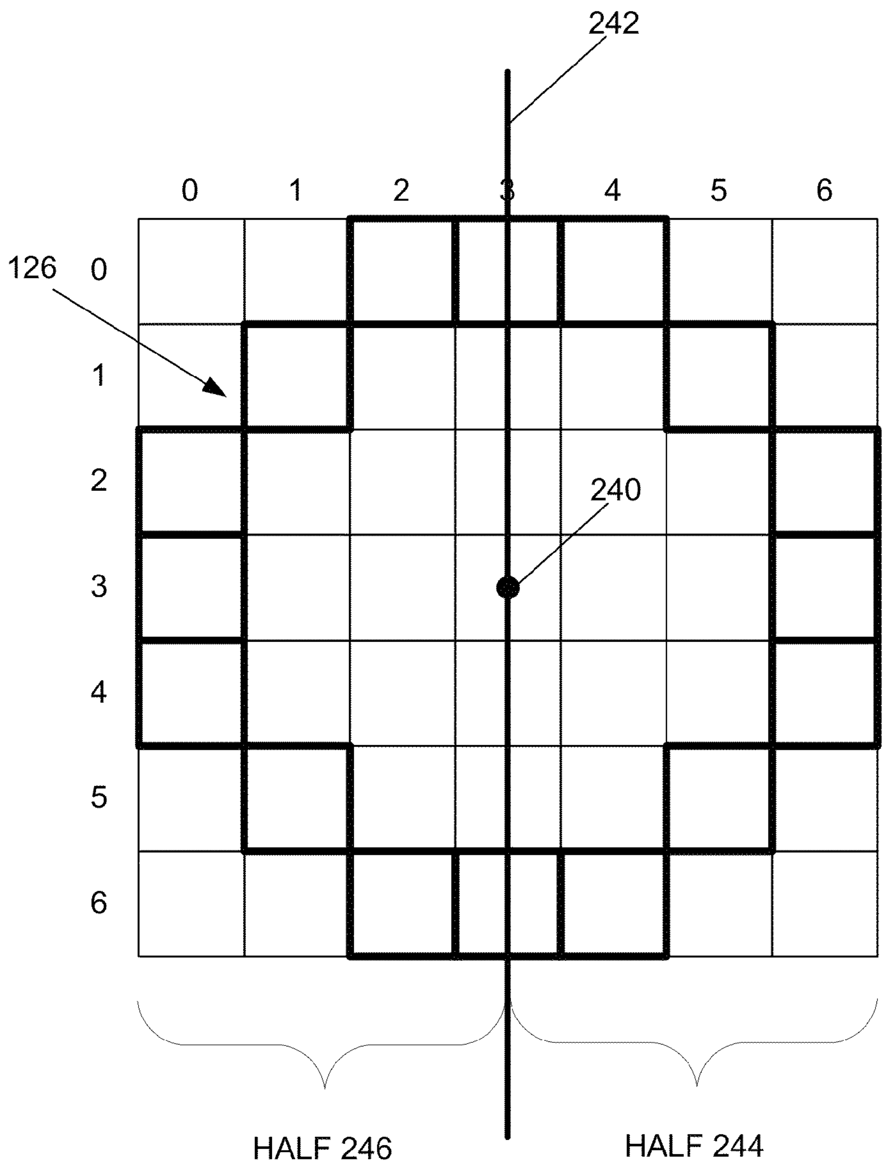

FIG. 10

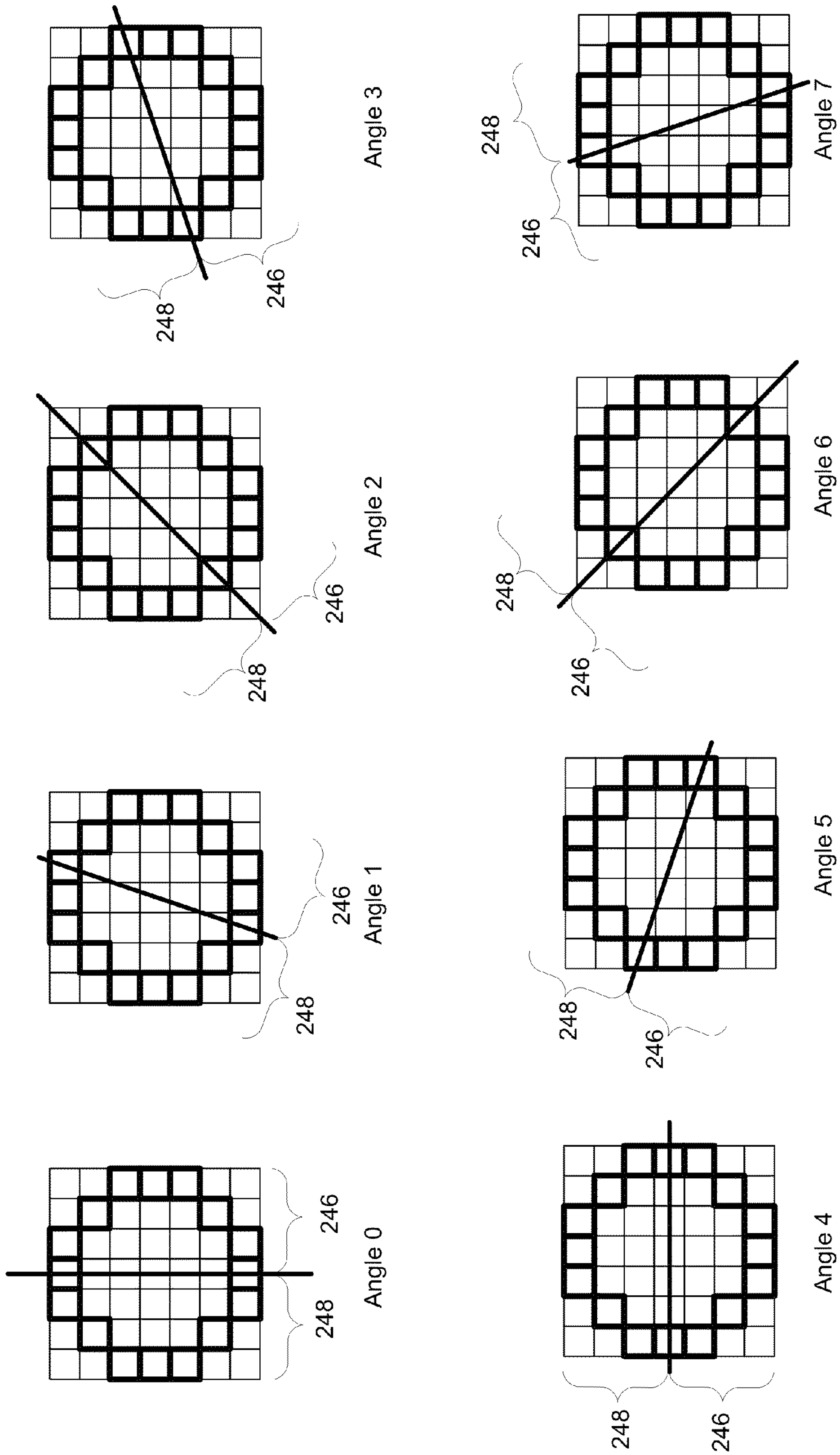
Angle 0
246
248
Angle 1
246
248
Angle 2
246
248
Angle 3
246
248
Angle 4
248
246
Angle 5
248
246
Angle 6
248
246
Angle 7
248
246

FIG. 11

250

PIXEL COORDINATE (252)	ANGLE (254)	MAGNITUDE (256)
(3,3)	0	1248
(3,4)	0	1297
(3,5)	1	1324

FIG. 12

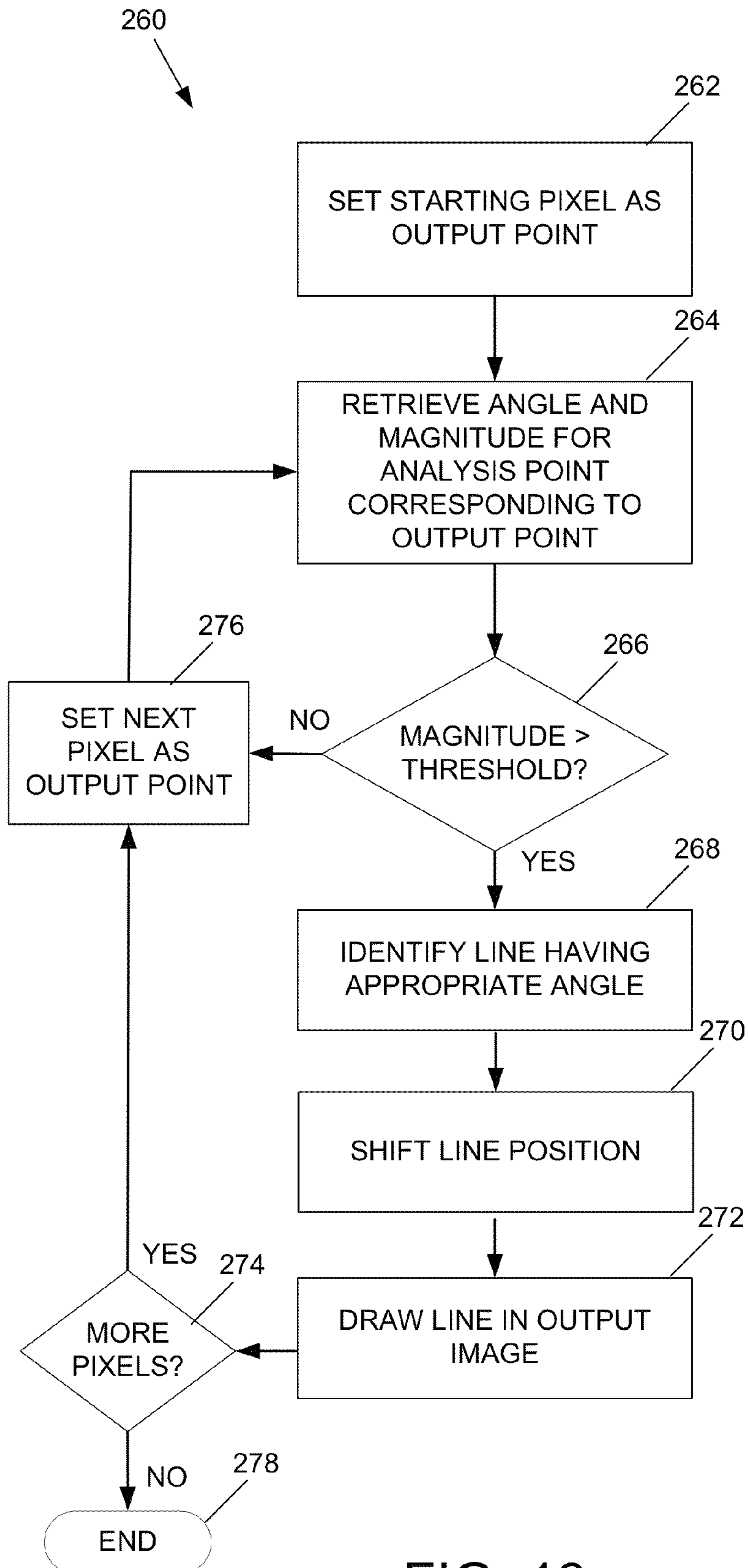
260
262
SET STARTING PIXEL AS OUTPUT POINT
264
RETRIEVE ANGLE AND MAGNITUDE FOR ANALYSIS POINT CORRESPONDING TO OUTPUT POINT
266
MAGNITUDE > THRESHOLD?
NO
276
SET NEXT PIXEL AS OUTPUT POINT
YES
268
IDENTIFY LINE HAVING APPROPRIATE ANGLE
270
SHIFT LINE POSITION
272
DRAW LINE IN OUTPUT IMAGE
274
MORE PIXELS?
YES
NO
278
END

FIG. 13

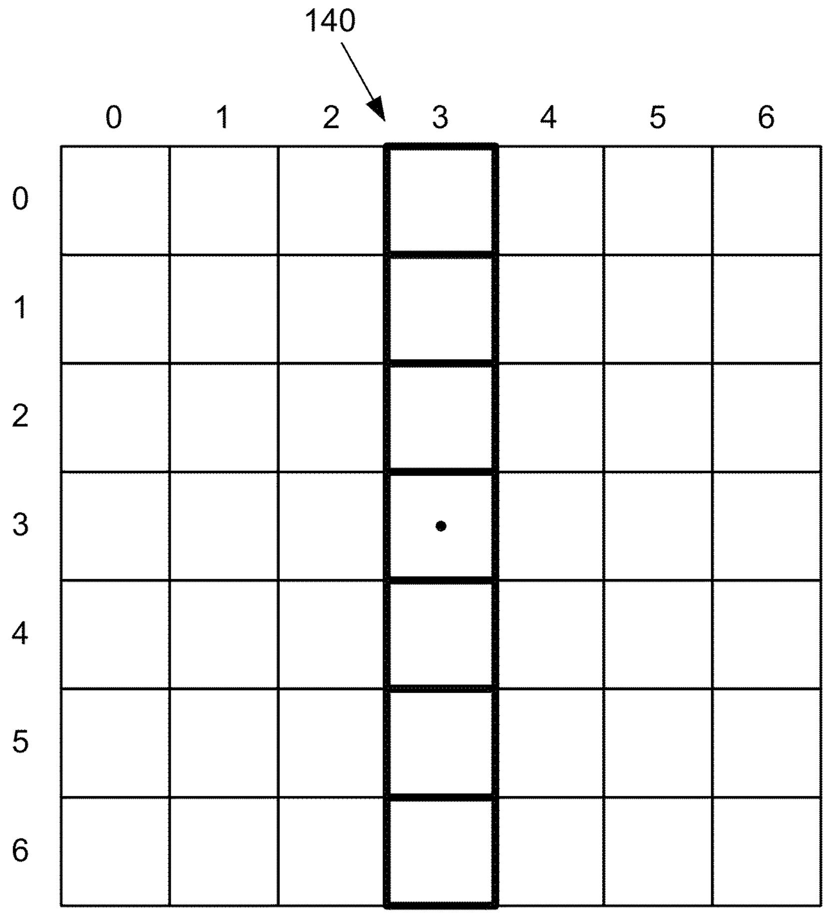

FIG. 14

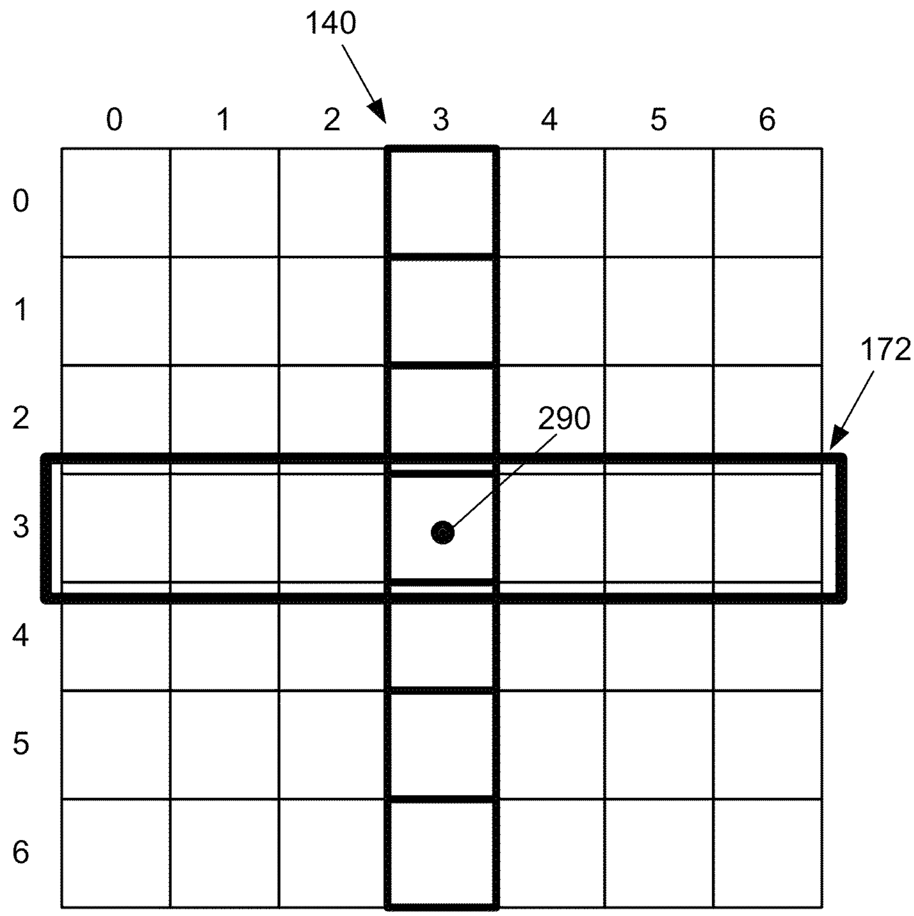

FIG. 15

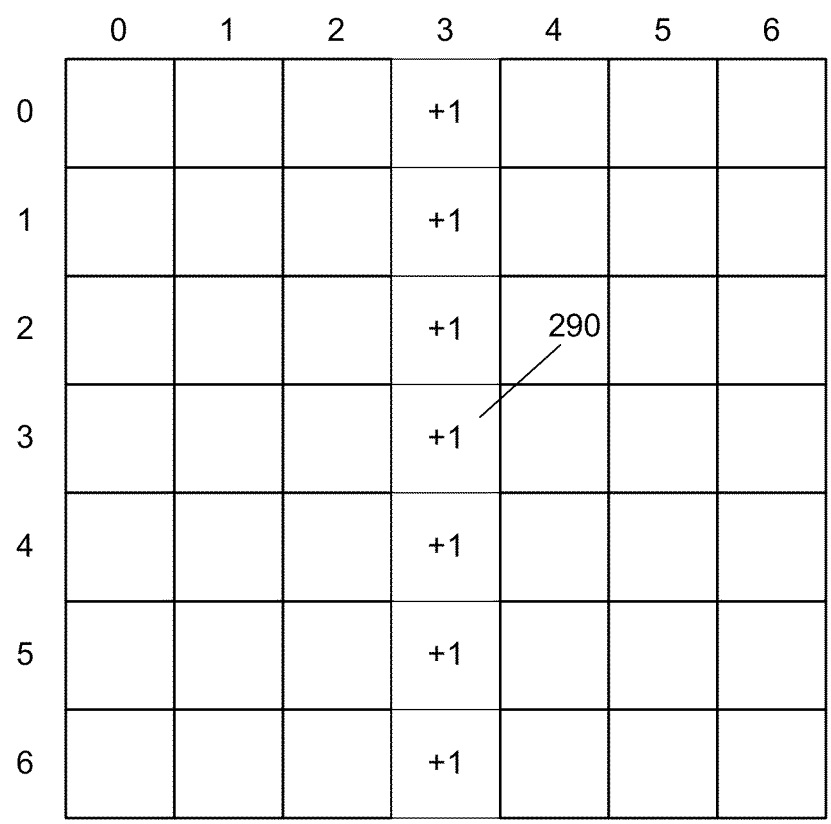

FIG. 16

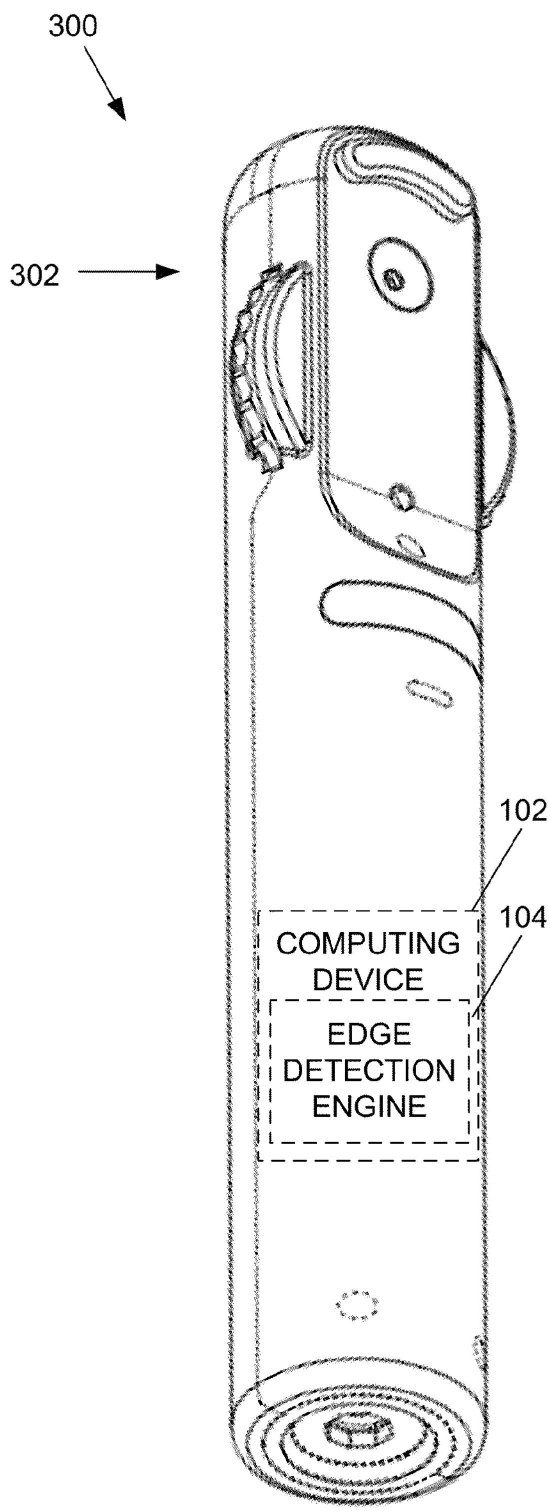

FIG. 17

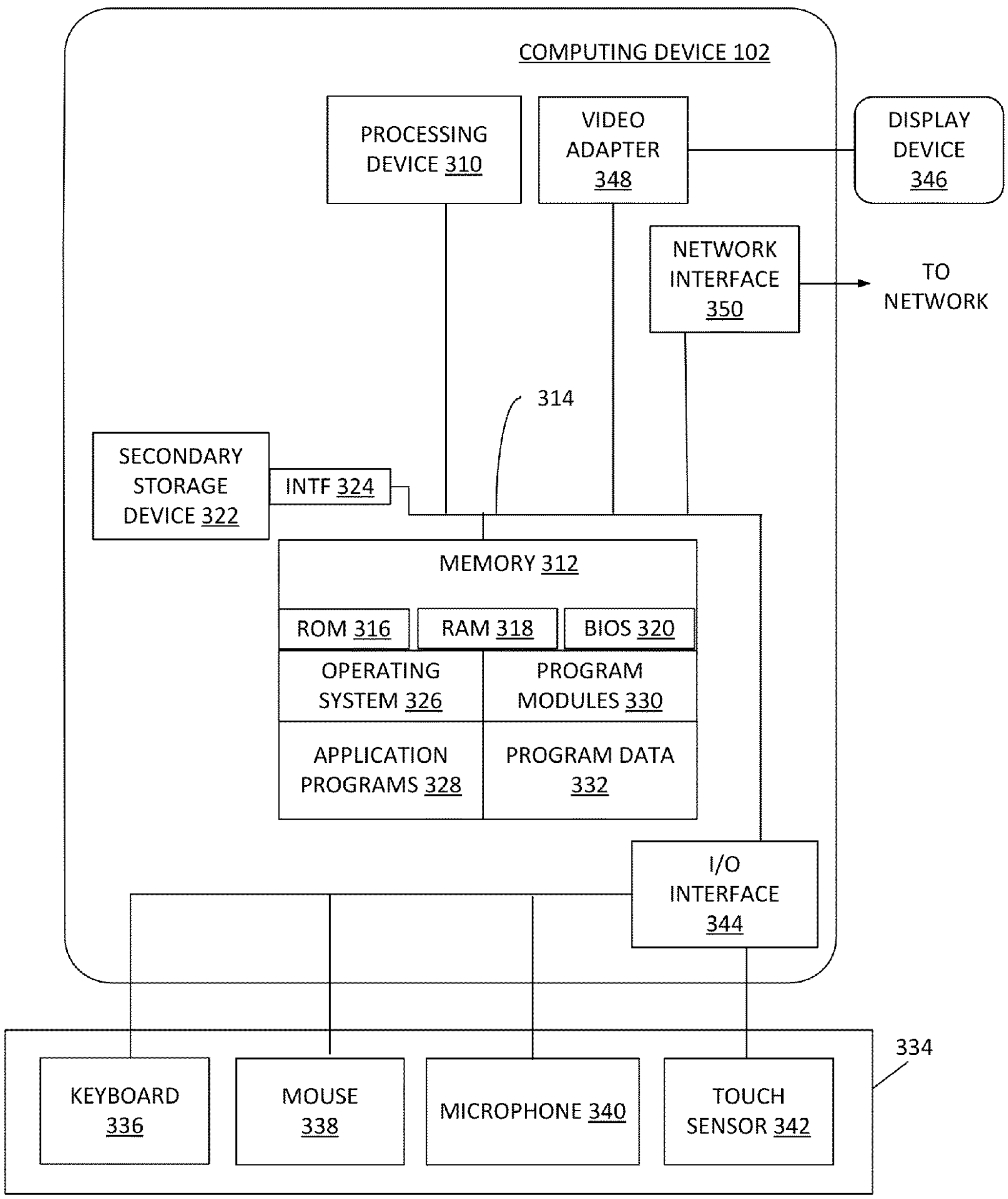
COMPUTING DEVICE 102
PROCESSING DEVICE 310
VIDEO ADAPTER 348
DISPLAY DEVICE 346
NETWORK INTERFACE 350
TO NETWORK
314
SECONDARY STORAGE DEVICE 322
INTF 324
MEMORY 312
ROM 316
RAM 318
BIOS 320
OPERATING SYSTEM 326
PROGRAM MODULES 330
APPLICATION PROGRAMS 328
PROGRAM DATA 332
I/O INTERFACE 344
334
KEYBOARD 336
MOUSE 338
MICROPHONE 340
TOUCH SENSOR 342

FIG. 18

EDGE DETECTION IN IMAGES

BACKGROUND

The human eyes and brain are very good at detecting points of interest in a visual image. One way that an object is identified in an image is by the identification of edges within the image. The brain can identify edges of the object by finding points in the image where adjacent pixels exhibit a distinct contrast. Numerous edges in the image combine to create an overall shape. The shape in the image is then compared with the shapes of known objects. If the shape is sufficiently similar to a known object, the brain can identify the object in the image.

Computers cannot process images in the same way as the human brain. Often images lack sufficient detail or contrast for a computer to be able to detect relevant features. Even the fundamental step of identifying the location of edges within an image can be challenging to perform with a computer. Without an adequate identification of the locations of edges in an image, the computer is unable to perform subsequent operations, such as identifying objects or other points of interest within the image.

SUMMARY

In general terms, this disclosure is directed to edge detection in images. In one possible configuration and by non-limiting example, the edge detection involves scanning the image using an annular aperture. Various aspects are described in this disclosure, which include, but are not limited to, the following aspects.

One aspect is a method of detecting edges within a digital image, the method comprising: processing at least a portion of the digital image, using a computing device, in a pixel-by-pixel manner including at an analysis point in the digital image, by: identifying pixels surrounding the analysis point; identifying a location of a bisection that divides the pixels surrounding the analysis point into two halves; determining an angle of the bisection that maximizes a difference in intensities of the pixels between the two halves; and determining that an edge is present in the digital image at the angle of the bisection.

Another aspect is an edge detection system comprising: a computing device comprising: a processing device; and a computer readable storage device storing data instructions that, when executed by the processing device generates an edge detection engine comprising: an annular aperture generator that operates to generate an annular aperture using a circle drawing algorithm; a line generator that generates lines representative of a set of bisectors of the annular aperture; an image scanning engine that utilizes the annular aperture as a mask to scan a digital image and identify edges within the digital image; and an output data generator that utilizes the lines to represent the edges in the output image.

A further aspect is a medical instrument comprising: an image capture device operable to capture an input image; and a computing device including an edge detection engine, the edge detection engine operable to process the input image to detect edges within the input image by processing the image using an annular aperture mask.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic diagram illustrating an example of an edge detection system.

FIG. **2** is a schematic block diagram illustrating an example of an edge detection engine of the edge detection system shown in FIG. **1**.

FIG. **3** is a flow chart illustrating an example method of generating an annular aperture.

FIG. **4** is a schematic diagram illustrating an example of the annular aperture.

FIG. **5** is a flow chart illustrating an example method of generating a plurality of lines representing a set of possible bisections of the annular aperture shown in FIG. **4**.

FIG. **6** is a schematic diagram illustrating an example set of linear bisections for the example annular aperture shown in FIG. **4**.

FIG. **7** is a flow chart illustrating an example method of scanning an image using the annular aperture shown in FIG. **4**.

FIG. **8** is a flow chart illustrating an example method of scanning an image for edge locations using the annular aperture shown in FIG. **4**.

FIG. **9** is a schematic diagram illustrating an example of a starting pixel of an input image, and also showing an example of pixels of an image that are within the annular aperture.

FIG. **10** is a schematic diagram illustrating an operating in which the annular aperture is bisected along a bisection line to group the pixels within the annular aperture into two halves.

FIG. **11** is a schematic diagram illustrating an example operation that determines an angle of the bisection that maximizes a difference in intensities between the two halves.

FIG. **12** illustrates an example of an angle and magnitude map.

FIG. **13** is a flow chart illustrating an example method of generating an output image identifying the locations of edges in an input image.

FIG. **14** is a schematic diagram illustrating an example of a line retrieved from the set of linear bisections shown in FIG. **6**.

FIG. **15** is a schematic diagram illustrating an example of an operation to shift a line to an actual location of an edge in an input image.

FIG. **16** is a schematic diagram illustrating an example operation to draw a line in the output image.

FIG. **17** is a perspective view of an example instrument in which aspects of the present disclosure can be implemented.

FIG. **18** illustrates an example of a computing device that can be used to implement aspects of the present disclosure.

DETAILED DESCRIPTION

Various embodiments will be described in detail with reference to the drawings, wherein like reference numerals represent like parts and assemblies throughout the several views. Reference to various embodiments does not limit the scope of the claims attached hereto. Additionally, any examples set forth in this specification are not intended to be limiting and merely set forth some of the many possible embodiments for the appended claims.

FIG. **1** is a schematic diagram illustrating an example of an edge detection system **100**. In this example, the edge detection system **100** includes a computing device **102** that executes an edge detection engine **104**. Also shown are an input image **106** and an output image **108**.

The edge detection system **100** can be implemented in multiple different forms. In one embodiment, for example, the edge detection system **100** is part of an instrument, such as a medical instrument. One example of a medical instrument is an ophthalmoscope, such as shown in FIG. **17**. Another example of a medical instrument is a colposcope. In these examples, the computing device **102** can be part of the instrument, for example. In another embodiment, the edge detection system **100** is implemented in a computing device **102** separate and distinct from an instrument. For example, in some embodiments the computing device **102** is a computer or part of a computer.

The computing device **102** typically includes at least a processing device and a computer-readable storage device. In some embodiments the computer-readable storage device stores data instructions, which when executed by the processing device, causes the processing device to perform one or more of the functions, methods, or operations, of the edge detection engine **104** described herein. An example of a computing device **102** is illustrated and described in more detail with reference to FIG. **18**.

The edge detection engine **104** operates to detect edges in an input image **106**. In some embodiments the results of the edge detection are output in the form of an output image **108**, which contains data identifying the locations of the edges detected in the input image **106**.

In some embodiments, the input image **106** is captured by an instrument, such as a medical instrument. In the example shown in FIG. **1**, the input image **106** is an image of an eye captured from an ophthalmoscope. The input image **106** can also come from other sources. Typically the input image **106** is captured by an image capture device, such as a charge-coupled device or a complementary metal-oxide-semiconductor active pixel sensor.

In some embodiments the input image **106** is stored in the computer-readable storage device in the form of an image file. The image can be encoded according to one or more of various image file formats. One example of a suitable image file format is the Joint Photograph Expert Group (JPEG) file format. Other examples of image file formats include exchangeable image file format (EXIF), tagged image file format (TIFF), raw image format (RAW), portable network graphics (PNG) format, graphics interchange format (GIF), bitmap file format (BMP), and portable bitmap (PBM) format. Other embodiments utilize other image file formats. The input data could also be provided in a non-image file format, such as utilizing another data format to convey the image data.

In some embodiments each pixel of the input image **106** is encoded in multiple color channels, such as red, green, and blue color channels. The color channels include an intensity value that indicates the relative contribution of that color to the pixel color. In other words, each pixel is represented by an intensity value within each color channel. The intensity values typically range from 0 to 255, for example. So, for example, a pixel that is primarily red will have a large intensity value in the red color channel and smaller intensity values in the blue and green color channels. A white pixel will have approximately equal intensities in all three color channels.

In some embodiments only one color channel of the input image **106** is used by the edge detection engine **104**. For example, to evaluate red features (e.g., oxygenated blood) within the eye, the red color channel of the input image **106** can be used. To evaluate blue features (e.g., a vein), the blue color channel of the input image **106** can be used. In other embodiments, two or more of the color channels are used. Further, some embodiments involve a color space transformation. Such a transformation can be used to evaluate other colors, such as cyan, magenta, and/or yellow, for example.

Hue, saturation, and/or brightness are used in some embodiments.

The output image **108** is generated by the edge detection engine **104**, and includes data that identifies the locations of edges detected in the input image **106**. In some embodiments the pixels in the output image **108** include intensity values. The more distinct the edge is in the input image **106**, the larger the intensity value will be at the corresponding point in the input image **106**. In some embodiments the output image **108** is also encoded in an image file format, such as the JPEG file format, or another format.

FIG. **2** is a schematic block diagram illustrating an example of the edge detection engine **104**. In this example, the edge detection engine **104** includes an annular aperture generator **110**, a line generator **112**, an image scanning engine **114**, and an output data generator **116**.

The annular aperture generator **110** operates to define an annular aperture. In some embodiments the edge detection engine **104** utilizes the annular aperture to scan the input image **106** to identify edges in the input image, as discussed in further detail below. An example of the annular aperture generator **110** is discussed in further detail herein with reference to FIGS. **3-4**.

The line generator **112** operates to define a set of lines. More specifically, in some embodiments the line generator **112** determines all of the possible ways that the annular aperture (generated by the annular aperture generator **110**) can be bisected, and generates a set of lines defining each of the possible bisections. In another possible embodiment, the line generator **112** is operated to generate specific lines as needed. An example of the line generator **112** is discussed in further detail with reference to FIGS. **5-6**.

The image scanning engine **114** operates to scan the input image **106**, shown in FIG. **1**, to detect edges in the input image **106**. An example of the image scanning engine **114** is discussed in further detail with reference to FIGS. **7-12**.

The output data generator **116** operates to generate an output of the edge detection engine **104**. In some embodiments the output data generator **116** generates the output image **108**, shown in FIG. **1**. The output data generator **116** is discussed in further detail with reference to FIGS. **13-16**.

FIGS. **3-4** illustrate examples of the annular aperture generator **110**, shown in FIG. **2**.

FIG. **3** is a flow chart illustrating an example method **120** of generating an annular aperture. In some embodiments the method **120** is performed by the annular aperture generator **110**, shown in FIG. **2**. In this example, the method **120** includes an operation **122** and an operation **124**.

The operation **122** is performed to determine a radius of an annular aperture to be generated. In some embodiments the radius is of a predetermined size. In other embodiments the radius is a selectable parameter. For example, in some embodiments the annular aperture generator **110** prompts a user to enter a desired radius. The optimum radius dimension will typically depend on multiple factors, such as the resolution of the input image **106**, the size and complexity of the features of interest in the input image **106**, and the level of noise (e.g., unimportant details) in the input image **106**. As one example, the radius is in a range from about 5 pixels to about 25 pixels. In some embodiments the radius is about 10 pixels.

Some embodiments utilize other parameters. For example, another possible parameter is the thickness of the annular aperture. In other embodiments, the annular aperture has a predetermined thickness, such as a thickness of one pixel.

The operation **124** is performed to generate the annular aperture. Because of the grid-like arrangement of pixels in an image, a perfect circular shape cannot be drawn using pixels. Accordingly, in some embodiments the operation **124** determines pixel locations for the annular aperture that approximate a circular shape. An example of operation **124** is illustrated in FIG. **4**.

FIG. **4** is a schematic diagram illustrating an example of an annular aperture **126**. A plurality of pixels **128** is also shown. The annular aperture **126** is formed within the plurality of pixels **128**, in some embodiments.

In this example, the desired annular aperture **126** has a radius R and is in the shape of a circle C.

Because the annular aperture **126** needs to be defined within the plurality of pixels **128**, which are arranged in a grid-like configuration, it is not possible for a perfectly circular annular aperture **126** to be generated. As a result, the operation **124** (shown in FIG. **3**) is performed to determine pixel locations for the annular aperture that approximate the shape of the circle C.

In some embodiments, the pixel locations are determined using a circle drawing algorithm. One example of a circle drawing algorithm is the midpoint circle algorithm, also known as the Bresenham's circle algorithm. Other embodiments utilize other circle drawing algorithms.

Using the circle drawing algorithm with a known radius R (e.g., a radius of 7), the annular aperture **126** is generated as represented by the pixels shown in bold lines in FIG. **4**. The annular aperture **126** has a shape that approximates the shape of the circle C and has a radius R and a thickness of one pixel.

The annular aperture **126** generated by the annular aperture generator **110** (FIG. **2**) is stored for subsequent use.

FIG. **5** is a flow chart illustrating an example method **130** of generating a plurality of lines representing the set of possible bisections of the annular aperture shown in FIG. **4**. In this example the method **130** includes operations **132** and **134**. In some embodiments the operations **132** and **134** are performed by the line generator **112**, shown in FIG. **104**.

The operation **132** is performed to determine a set of possible linear bisections of an annular aperture. An example of the annular aperture is shown in FIG. **4**.

Before searching through the image for possible edges, the operation **132** can be performed to identify the possible shapes of those edges. In other words, the edge might be a vertical line extending from the top to the bottom of the annular aperture, or it could be a horizontal line extending from the left to the right of the aperture. The edge could also be present at some other angle. Because the digital image has a limited number of pixels, the quantity of lines that can be formed within the annular aperture is limited. In some embodiments, the lines are determined by starting at a first pixel of the annular aperture **126** and identifying a line that can be drawn from that point to the corresponding point directly opposite that point. The process is then repeated consecutively for each point around the annular aperture until all possible angles have been evaluated. An example of the set of possible linear bisections is shown in FIG. **6**.

The operation **134** is performed to determine pixel locations for each linear bisection. Stated another way, the operation **134** is performed to draw each of the lines between opposing points of the annular aperture **126**.

Because of the grid-like arrangement of the pixels, straight lines can only be drawn vertically and horizontally in the pixels. A straight line having an angle that is not vertical or horizontal cannot be perfectly represented in the pixels. Therefore, in some embodiments the operation **134** involves the use of a line drawing algorithm. One example of a line drawing algorithm is the Bresenham's line algorithm. The line drawing algorithm determines a set of pixels that form an approximation to a perfect line extending between two opposing points of the annular aperture.

FIG. **6** is a schematic diagram illustrating an example set **138** of linear bisections for the example annular aperture **126** shown in FIG. **4**.

In this example, the set **138** of linear bisections are formed by identifying all straight lines that can bisect the annular aperture **126** (FIG. **4**) at various angles. One way to do this is to begin with a starting pixel of the annular aperture **126**, such as the pixel **144**, draw the linear bisector extending from this pixel to the corresponding pixel on the opposite side of the annular aperture **126**, and then consecutively rotate through the adjacent pixels of the annular aperture **126** in the same manner until all possible bisections have been identified. The number of possible bisections varies depending on the pixel size of the annular aperture **126**. In this example, the annular aperture has a diameter of seven pixels, and eight possible bisections, as shown.

Each linear bisection can be identified by an angle of the bisection with respect to a starting location. In this example the angles are identified by a number of pixels around the annular aperture, such that angle **0** is the angle of a linear bisection passing through a first pixel (**144**) of the annular aperture, angle **1** is the angle of a linear bisection passing through a second pixel (**152**) of the annular aperture, and so on.

Although it is possible to convert the angles to degrees, the conversion would require additional processing steps that are unnecessary. As one example, however, the annular aperture can be bisected by eight different lines, such that the angle between each adjacent pixel of the annular aperture is 22.5 degrees (180/8=22.5). Note that the linear bisections from 0 to 180 degrees are the same as the linear bisections from 180 to 360 degrees, such that the computation of one set of the linear bisections is adequate to address all possible linear bisections of the annular aperture.

The first linear bisection **140** in the set **138**, with an angle **0** (0 degrees), is the approximation of a line **142** extending vertically across the annular aperture. The linear bisection extends from pixel **144** to the corresponding opposite pixel **146**. The linear bisection **140** includes seven pixels from pixel **144** to pixel **146**.

The next linear bisection **148**, with an angle **1** (22.5 degrees), is the approximation of a line **150** extending from the next pixel **152** in the clockwise direction from the first pixel **144**, to the corresponding opposite pixel **154**. In this example it can be seen how the line **150** cannot be perfectly represented in the pixels, and therefore a set of seven pixels extending from pixel **152** to pixel **154** are selected to best approximate the line **150**.

The next linear bisection **156**, with an angle **2** (45 degrees), is the approximation of a line **158**. The linear bisection includes seven pixels extending from pixel **160** to pixel **162**.

The linear bisection **164** has an angle A**3** (67.5 degrees), and is the approximation of a line **166**. The linear bisection extends from a pixel **168** to a pixel **170**.

The linear bisection **172** is an approximation of the horizontal line **174** having an angle **4** (90 degrees), which extends from pixel **176** to pixel **178**.

The next linear bisection **180** has an angle A**5** (112.5 degrees), and is the approximation of a line **182**. The linear bisection **180** extends from pixel **184** to pixel **186**.

The linear bisection **188** has an angle A**6** (135 degrees), and is the approximation of a line **190**. The linear bisection **188** extends from pixel **192** to pixel **194**.

At angle A7 (157.5 degrees) is the linear bisection **196** that approximates the line **198**. The linear bisection extends from pixel **200** to pixel **202**.

Advancing to the next pixel around the annular aperture arrives at pixel **146**, and the linear bisection from pixel **146** is the same as the line **140** at angle **0**. Therefore, all linear bisections have been identified for the example annular aperture **126**, shown in FIG. **4**. Larger annular apertures will have a larger quantity of linear bisections, while smaller annular apertures will have a smaller quantity of linear bisections.

In some embodiments the set **138** of linear bisections is stored in a computer readable storage device for subsequent use.

FIG. **7** is a flow chart illustrating an example method **210** of scanning an image using an annular aperture. In this example, the method **210** includes operations **212** and **214**. In some embodiments the operations **212** and **214** are performed by an image scanning engine **114**, shown in FIG. **2**.

The operation **212** is performed to scan an image **106** (FIG. **1**) for edge locations using an annular aperture. An example of operation **212** is illustrated and described in more detail with reference to FIGS. **8-12**.

The operation **214** is performed to generate an output image **108** (FIG. **1**) identifying the edge locations. An example of operation **214** is illustrated and described in more detail with reference to FIGS. **13-16**.

FIG. **8** is a flow chart illustrating an example method **220** of scanning an image for edge locations using an annular aperture. FIG. **8** also illustrates an example of the operation **212**, shown in FIG. **7**. In this example, the method **220** includes operations **222**, **224**, **226**, **228**, **230**, **232**, **234**, and **236**.

The method **220** is performed to scan an input image, such as the image **106**, shown in FIG. **1**, to identify edges within the image **106**. As described herein, in some embodiments the method **220** involves scanning only a single color channel of the input image **106**. For example, the red color channel can be evaluated. Within the red color channel, each pixel of the image **106** is represented by an intensity value. The intensity value can be a value between 0 and 255, for example. The intensity value indicates the brightness of the color associated with the color channel (e.g., red) in the pixel.

The operation **222** is performed to determine a starting pixel, and to begin the scanning and analysis of the image at that point. For example, the starting pixel can be the upper left pixel of the image.

A problem with edge or corner pixels, however, is that evaluation of such pixels requires that the annular aperture **126** (FIG. **4**) be positioned such that the annular aperture **126** extends outside of the bounds of the image. In such a case, it is desirable to know what the background color is in the image. For example, if it is known that the background is black, the evaluation can proceed by using a default intensity value corresponding with the background color (e.g., an intensity of zero, representing a dark pixel).

Alternatively, pixels that are less than the radius of the annular aperture **126** (FIG. **4**) away from the edge are omitted from processing in method **220**. For an annular aperture having a diameter of 7 pixels, for example, the starting pixel can be the pixel that is four pixels down and four pixels to the right of the upper left pixel. An example is shown in FIG. **9**. Various other starting points could also be used in other embodiments.

Once the starting point has been determined and set as the first analysis point in the image **106**, the operation **224** is performed to identify pixels surrounding the analysis point using the annular aperture **126** (FIG. **4**). To do so, the annular aperture **126** is used as a mask layer to identify only those pixels in the image **106** that are within the annular aperture **126** when the annular aperture **126** is centered on the analysis point. An example is shown in FIG. **9**.

The operation **226** is performed to bisect the annular aperture **126** to group the pixels into two halves. An example of operation **226** is shown in FIG. **10**.

The operation **228** is performed to determine an angle of the bisection that maximizes a difference in intensities between the two halves. To do so, the intensity values for each pixel within a first half of the annular aperture **126** are added together, and the intensity values for each pixel within the second half of the annular aperture **126** are also added together. The combined intensity value of the first half is then compared with the combined intensity value of the second half to determine a difference between the intensity values.

The same process is repeated for each possible bisection of the annular aperture **126**, and the differences between the intensity values are determined for each possible bisection. An example is illustrated in FIG. **11**.

If a large difference in the intensity values is found for a given bisection, the difference indicates the likely presence of an edge within the image **106** at or near the location of the analysis point.

The operation **228** identifies the bisection angle that results in the greatest difference in the intensity value between the two halves.

In operation **230**, the angle that results in the greatest difference is then stored in a computer readable storage device for the analysis point, along with the intensity value difference. The different in the intensity values between the two halves is sometimes referred to herein as a magnitude. In some embodiments the angle and magnitude are stored in an angle and intensity map. An example of an angle and intensity map is shown in FIG. **12**.

Once the angle and the magnitude have been computed and stored for the analysis point, operation **232** determines whether there are additional pixels that need to be analyzed. If so, operation **234** sets the next pixel as the analysis point and repeats operations **224**, **226**, **228**, **230**, and **232** accordingly. Otherwise the method **220** ends at operation **236**.

FIG. **9** is a schematic diagram illustrating an example of a starting pixel of an input image **106**, and also showing an example of the pixels of the image that are within the annular aperture **126**. Only an upper left portion of the image **106** is represented in FIG. **9**.

In this example, the annular aperture has a diameter of seven pixels. As a result, any pixels that are located less than the radius (3.5 pixels) of the annular aperture away from the edge of the image are designated as edge pixels. If the annular aperture were centered on an edge pixel, a portion of the annular aperture would extend outside of the bounds of the image. In some embodiments the scanning of the image involves the use of interior pixels that are greater than the radius of the annular aperture **126** away from the bounds of the image.

In some embodiments each pixel of the image **106** is represented by a coordinate value of (X,Y), where X is the horizontal number of pixels from the left side of the image and Y is the vertical number of pixels from the top of the image. The upper left pixel has a coordinate (0,0).

In this example, the pixel (3,3) is selected as the starting pixel, and is therefore set as the first analysis point **240**.

The annular aperture **126** is then used to identify a set of pixels surrounding the analysis point that are within the annular aperture **126**. In FIG. **9** the pixels within the annular aperture are represented with bold lines.

FIG. **10** is a schematic diagram illustrating an example of operation **226**, shown in FIG. **8**, during which the annular aperture **126** is bisected along a bisection line **242** to group the pixels within the annular aperture **126** into two halves **244** and **246**.

The annular aperture **126** is bisected along a bisection line **242**. The example shown in FIG. **10** illustrates a vertical bisection line **242**. The vertical bisection line **242** divides the annular aperture **126** into two halves **244** and **246**, permitting the pixels within the annular aperture **126** to be grouped according to the corresponding halves **244** and **246**.

FIG. **11** is a schematic diagram illustrating an example of operation **248**, shown in FIG. **8**, which determines an angle of the bisection that maximizes a difference in intensities between the two halves **246** and **248**.

In this example, the annular aperture is bisected along all possible bisection lines from the angle **0** to the angle **7**. For each bisection, a sum of the intensities of the pixels in the half **246** is compared with a sum of the intensities of the pixels in the half **248**, and a difference between the intensity values is computed. The bisection angle that results in the greatest difference between the two halves is then identified.

FIG. **12** illustrates an example of an angle and magnitude map **250**, such as generated by the method **220**, shown in FIG. **8**. Only a representative portion of an example angle and magnitude map **250** is shown in FIG. **12**.

In this example, the angle and magnitude map **250** includes pixel coordinates **252**, angles **254**, and magnitudes **256**.

The pixel coordinate **252** identifies an analysis point of the image.

The angle **254** identifies the bisection angle that was found to result in the greatest difference in intensities between the two halves of the annular aperture for the analysis point identified by the pixel coordinate **252**.

The magnitude **256** identifies the difference in intensities that was computed at the angle **254** for the analysis point identified by the pixel coordinate **252**.

FIG. **13** is a flow chart illustrating an example method **260** of generating an output image **108** (shown in FIG. **1**) identifying the locations of edges in an input image **106** (also shown in FIG. **1**). FIG. **13** also illustrates an example of the operations performed by some embodiments of the output data generator **116**, shown in FIG. **2**. In this example the method **260** includes operations **262**, **264**, **266**, **268**, **270**, **272**, **274**, **276**, and **278**.

The method **260** is performed to generate the output image **108**, which identifies edges within the input image **106**. To do so, the output image **108** is processed on a pixel-by-pixel basis, just as the input image was processed on a pixel-by-pixel basis (such as in the example method **220**, shown in FIG. **8**). For each analysis point of the input image **106**, a corresponding output point of the output image is processed by the method **260**.

The operation **262** begins by setting a starting pixel as the first output point. In some embodiments the same starting point is used in operation **262** as in the operation **222** shown in FIGS. **8** and **9**, except that the output point identifies the corresponding pixel of the output image **108** rather than the input image **106**. Typically the same pixel coordinates are used to identify the pixels in the input and output images **106** and **108** so that a coordinate of an output point of the output image **108** corresponds to the same coordinate of the analysis point of the input image **106**.

The operation **264** is performed to retrieve an angle and magnitude for the analysis point corresponding to the output point from the angle and magnitude map **250** (FIG. **12**).

The operation **266** is then performed to determine whether the magnitude exceeds a threshold value. If the magnitude does not exceed the threshold, it is determined that the input image **106** does not contain a sufficiently distinct edge at or near to the output point, and therefore method **260** continues with operation **267** to advance to the next pixel.

If the magnitude exceeds the threshold, then it is determined that the input image **106** does contain a sufficiently distinct edge at or near to the output point, and therefore the method **260** continues with operation **268**.

The operation **268** is performed to identify a line having the same angle as the retrieved angle for the analysis point. In some embodiments the line is retrieved from the set **138** of linear bisections, such as shown in FIG. **6**. For example, if the retrieved angle is angle **0**, the line **140** is retrieved. An example is illustrated in FIG. **14**.

Some embodiments include an operation **270** that operates to shift the line position. Other embodiments do not include the operation **270**, such that the method **260** proceeds directly to operation **272**.

Even though a significant difference between the intensity values may exist for the analysis point of the input image **106**, the position of the edge in the image is not necessarily centered exactly at the analysis point. Therefore, in some embodiments the operation **270** is performed to shift the line position to the actual location of the edge in the input image. An example of operation **270** is illustrated in FIG. **15**.

Once the appropriate location of the line has been determined, the operation **272** is performed to draw the line in the output image **108**. An example of operation **272** is shown in FIG. **16**.

The operation **274** is performed to determine whether additional pixels remain to be processed. If so, operation **276** is performed to set the next pixel as the output pixel and operations **264**, **266**, **268**, **270**, **272**, and **274** are repeated accordingly.

FIG. **14** is a schematic diagram illustrating an example of the line **140** retrieved from the set **138** of linear bisections, such as shown in FIG. **6**.

FIG. **15** is a schematic diagram illustrating an example of the operation **270**, shown in FIG. **13**, which is performed to shift a line **140** to the actual location of the edge in the input image.

In this example, after retrieving the line **140** from the set **138** of linear bisections, a second line is retrieved. The second line is the line perpendicular to the line **140**. In this example, the line **172** (shown in FIG. **6**) is perpendicular to the line **140**, and therefore it is retrieved. The perpendicular line **172** is centered on the output point **290** of the output image **108**.

The magnitude of each pixel corresponding to the perpendicular line **172** in the angle and magnitude map **250** is then evaluated to identify the pixel having the greatest magnitude. This pixel is determined to be the proper location of the edge in the input image **106**. That pixel is then used in operation **272** as the center point for drawing the line **140** in the output image **108**.

FIG. **16** is a schematic diagram illustrating an example of the operation **272**, shown in FIG. **13**, which is performed to draw a line in the output image **108**.

In this example, the output point **290** is determined in operation **270** to have the greatest magnitude. Therefore, the operation **272** is performed to draw the line **140** in the output image **108**. In some embodiments, drawing the line involves increasing the intensity value of the pixels corresponding to the line **140**. In one example the intensity value is incremented by one.

Even though an increment of one may not be easily visually distinguishable to the human eye if the output image **108** is displayed on a display device, the intensity value can be read by a computing device to distinguish between a pixel having a value of 1 and another pixel having an intensity value of 2, for example. In some embodiments the output image **108** is not displayed, and instead is used for subsequent image processing by a computing device, such that it is not necessary for a human to be able to visually distinguish between different intensities. However, in other embodiments the intensity increments can be greater than one to permit differences in intensity values to be more easily visually distinguished by a human.

The line drawing process shown in FIG. **16** is then repeated for each additional pixel, as discussed with reference to FIG. **13**, until all remaining pixels have been processed. The resulting lines drawn in the output image **108** identify the locations of the edges in the input image **106**. An example of the output image **108** is shown in FIG. **1**.

FIG. **17** is a perspective view of an example instrument **300** in which aspects of the present disclosure can be implemented.

One example of an instrument **300** is a medical instrument. A more specific example of a medical instrument is an ophthalmoscope, as shown.

In some embodiments the instrument **300** includes an image capture device **302**. The image capture device **302** can be used to capture the input image **106**, for example.

In some embodiments the instrument **300** includes a computing device **102**. The computing device **102** includes the edge detection engine **104**, such as illustrated and described herein. Accordingly, in some embodiments the operations of the edge detection engine are performed by the instrument **300**.

In another embodiment, the computing device **102** and edge detection engine **104** can be separate from the instrument **300**. For example, the image **106** captured by the instrument **300** is transferred to the computing device **102** by a wired, wireless, or combination of wired and wireless communication system.

In some embodiments the instrument **300** is configured for connection with a docking station through which the transmission of the image **106** to the computing device **102** can occur. The image **106** may also be physically transferred via a computer readable storage device in yet another possible embodiment.

FIG. **18** illustrates another example of the computing device **102** that can be used to implement aspects of the present disclosure. For example, the computing device **102** illustrated in FIG. **18** can be used to execute application programs and/or software modules (including the software engines) described herein.

The computing device **102** typically includes at least one processing device **310** and at least one computer readable medium.

One example of a processing device is a central processing unit (CPU). Other embodiments include other processing devices. For example, some embodiments include a graphics processing unit (GPU). Other embodiments include compute unified device architecture (CUDA) cores or other single instruction multiple data (SIMD) devices that can assign resources to process pixels in parallel, which may be up to hundreds of times faster than a typical CPU. Yet other embodiments include a programmable gate array (PGA), complex programmable logic device (CPLDs), system on chip (SoCs), or application-specific integrated circuits (ASICs), for example.

The computing device **102** also typically includes at least some form of computer readable media. Computer readable media includes any available media that can be accessed by the computing device **102**. By way of example, computer readable media include computer readable storage media and computer readable communication media.

Computer readable storage media includes volatile and nonvolatile, removable and non-removable media implemented in any device configured to store information such as computer readable instructions, data structures, program modules or other data. Computer readable storage media includes, but is not limited to, random access memory, read only memory, electrically erasable programmable read only memory, flash memory or other memory technology, compact disc read only memory, digital versatile disks or other optical storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices, or any other medium that can be used to store the desired information and that can be accessed by the computing device **102**. Computer readable storage media does not include computer readable communication media.

Computer readable communication media typically embodies computer readable instructions, data structures, program modules or other data in a modulated data signal such as a carrier wave or other transport mechanism and includes any information delivery media. The term "modulated data signal" refers to a signal that has one or more of its characteristics set or changed in such a manner as to encode information in the signal. By way of example, computer readable communication media includes wired media such as a wired network or direct-wired connection, and wireless media such as acoustic, radio frequency, infrared, and other wireless media. Combinations of any of the above are also included within the scope of computer readable media.

Some embodiments include two or more computing devices. For example, a first computing device can be used for image acquisition, while another computing device is used for image processing. As another example, two or more computing devices can be used for image processing. Further, in some embodiments a single computing device includes multiple processors and multiple computer readable media, which may be remote from each other. Communication between the multiple components of one or more computing devices can occur across one or more communication networks, for example. Data can be transferred using one or more of a shared memory bus, Ethernet, Bluetooth, WiFi, or other data communication networks, for example.

In the illustrated example, the computing device **102** also includes a system memory **312**, and a system bus **314** that couples various system components including the system memory **312** to the processing device **310**. The system bus **314** is one of any number of types of bus structures including a memory bus, or memory controller; a peripheral bus; and a local bus using any of a variety of bus architectures.

Examples of computing devices suitable for the computing device **102** include a server, a desktop computer, a laptop computer, a tablet computer, a mobile computing device (such as a smart phone, an iPod® or iPad® mobile digital device, or other mobile devices), or other devices configured to process digital instructions.

In some embodiments the system memory **312** includes read only memory **316** and random access memory **318**. A basic input/output system **320** containing the basic routines that act to transfer information within computing device **102**, such as during start up, is typically stored in the read only memory **316**.

In the illustrated example the computing device **102** also includes a secondary storage device **322**, such as a hard disk drive, for storing digital data. The secondary storage device **322** is connected to the system bus **314** by a secondary storage interface **324**. The secondary storage devices **322** and their associated computer readable media provide nonvolatile storage of computer readable instructions (including application programs and program engines or modules), data structures, and other data for the computing device **102**.

Although the exemplary environment illustrated in FIG. **18** employs a hard disk drive as a secondary storage device **322**, other types of computer readable storage media are used in other embodiments. Examples of these other types of computer readable storage media include flash memory cards, compact disc read only memories, random access memories, or read only memories. Some embodiments include non-transitory media. Additionally, such computer readable storage media can include local storage or cloud-based storage.

A number of program modules can be stored in a secondary storage device **322** or memory **312**, including an operating system **326**, one or more application programs **328**, other program modules **330** (such as the software engines described herein), and program data **332**. The computing device **102** can utilize any suitable operating system, such as Microsoft Windows™, Google Chrome™, Apple OS, and any other operating system suitable for a computing device.

In some embodiments, a user provides inputs to the computing device **102** through one or more input devices **334**. Examples of input devices **334** include a keyboard **336**, mouse **338**, microphone **340**, and touch sensor **342** (such as a touchpad or touch sensitive display). Other embodiments include other input devices **334**. The input devices are often connected to the processing device **310** through an input/output interface **344** that is coupled to the system bus **314**. These input devices **334** can be connected by any number of input/output interfaces, such as a parallel port, serial port, game port, or a universal serial bus. Wireless communication between input devices and the interface **344** is possible as well, and includes infrared, BLUETOOTH® wireless technology, 802.11a/b/g/n, cellular, or other radio frequency communication systems in some possible embodiments.

In this example embodiment, a display device **346**, such as a monitor, liquid crystal display device, projector, or touch sensitive display device, is also connected to the system bus **314** via an interface, such as a video adapter **348**. In addition to the display device **346**, the computing device **102** can include various other peripheral devices (not shown), such as speakers or a printer.

When used in a local area networking environment or a wide area networking environment (such as the Internet), the computing device **102** is typically connected to a communication network through a network interface **350**, such as an Ethernet interface. Other possible embodiments use other communication devices. For example, some embodiments of the computing device **102** include a modem for communicating across the network.

The computing device illustrated in FIG. **18** is also an example of programmable electronics, which may include one or more such computing devices, and when multiple computing devices are included, such computing devices can be coupled together with a suitable data communication network so as to collectively perform the various functions, methods, or operations disclosed herein.

The various embodiments described above are provided by way of illustration only and should not be construed to limit the claims attached hereto. Those skilled in the art will readily recognize various modifications and changes that may be made without following the example embodiments and applications illustrated and described herein, and without departing from the true spirit and scope of the following claims.

What is claimed is:

1. A method of detecting edges within a digital image, the method comprising:

processing at least a portion of the digital image, using a computing device, in a pixel-by-pixel manner including at an analysis point in the digital image, by:

identifying pixels surrounding the analysis point;

identifying a location of a bisection that divides the pixels surrounding the analysis point into two halves;

determining an angle of the bisection that maximizes a difference in intensities of the pixels between the two halves;

determining that an edge is present in the digital image at the angle of the bisection; and

moving the analysis point sequentially across the pixels of at least a portion of the digital image and repeating the processing.

2. The method of claim **1**, wherein identifying pixels surrounding the analysis point involves the use of an annular aperture mask.

3. The method of claim **2**, wherein the annular aperture mask is generated using a circle drawing algorithm.

4. The method of claim **1**, wherein determining that an edge is present in the digital image comprises determining whether the difference in intensities between the two halves is greater than a threshold.

5. The method of claim **1**, further comprising generating an angle and magnitude map and storing the angle of the bisection and a magnitude of the difference in intensities of the pixels between the two halves in the angle and magnitude map for the analysis point.

6. The method of claim **1**, further comprising generating an output image after determining that an edge is present in the digital image.

7. The method of claim **6**, wherein generating output data comprises drawing a line in the output image at the angle of the bisection.

8. The method of claim **7**, further comprising:

checking a set of pixels perpendicular to the bisection before drawing the line to determine a point of greatest magnitude; and

shifting a position of the line to the point of greatest magnitude.

9. An edge detection system comprising:

a computing device comprising:

a processing device; and

a computer readable storage device storing data instructions that, when executed by the processing device generates an edge detection engine comprising:

an annular aperture generator that operates to generate an annular aperture using a circle drawing algorithm;

a line generator that generates lines representative of a set of bisectors of the annular aperture, wherein the line generator generates lines representative of the set of all possible bisectors of the annular aperture;

an image scanning engine that utilizes the annular aperture as a mask to scan a digital image and identify edges within the digital image; and

an output data generator that utilizes the lines to represent the edges in the output image.

10. The computing device of claim **9**, wherein the circle drawing algorithm is Bresenham's circle algorithm.

11. The computing device of claim **9**, wherein the annular aperture has a thickness of one pixel.

12. The computing device of claim **9**, wherein the annular aperture has a radius in a range from about 5 pixels to about 25 pixels.

13. The computing device of claim **9**, wherein the line generator utilizes Bresenham's line algorithm.

14. The computing device of claim **9**, wherein the image scanning engine generates an angle and magnitude map identifying an angle and a magnitude for potential edge identified in the digital image.

15. A medical instrument comprising:

an image capture device operable to capture an input image; and

a computing device including an edge detection engine, the edge detection engine operable to process the input image to detect edges within the input image by processing the image using an annular aperture mask, the edge detection engine being further operable to:

identify pixels surrounding an analysis point;

identify a location of a bisection that divides the pixels surrounding the analysis point into two halves:

determine an angle of the bisection that maximizes a difference in intensities of the pixels between the two halves; and

determine that an edge is present in the digital image at the angle of the bisection.

16. The medical instrument of claim **15**, wherein the medical instrument is an ophthalmoscope.

17. The medical instrument of claim **15**, wherein the medical instrument is a culposcope.

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